

## **Final Report**

**Title: MEASURING LIFT FORCE IN FLAPPING FLIGHT**

**AFOSR/AOARD Reference Number: AOARD—094101**

**AFOSR/AOARD Program Manager: Lt Col Dr. Seo, John S**

**Period of Performance: 2009-2010**

**Submission Date: May-2009**

**PI: Prof. SREENIVAS K R**  
Engineering Mechanics Unit  
Jawaharlal Nehru Centre for Advanced Scientific Research  
Bangalore-560064. INDIA

**Contact: +91-80-22082836**  
**krs@jncasr.ac.in**

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>08 FEB 2011</b>		2. REPORT TYPE <b>Final</b>		3. DATES COVERED <b>17-07-2009 to 17-07-2010</b>	
4. TITLE AND SUBTITLE <b>Lift Generation Mechanisms in Flapping Flight</b>				5a. CONTRACT NUMBER <b>FA23860914101</b>	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>K. R. Sreenivas</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Jawaharlal Nehru Centre for Advanced Scientific Research,Jakkur Post,Bangalore, Karnataka 560 064,India,NA,NA</b>				8. PERFORMING ORGANIZATION REPORT NUMBER <b>N/A</b>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) <b>AOARD, UNIT 45002, APO, AP, 96338-5002</b>				10. SPONSOR/MONITOR'S ACRONYM(S) <b>AOARD</b>	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) <b>AOARD-094101</b>	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>Objective of the research was to measure forces generated by flapping test-ring for rigid and wings having controlled flexibility to identify an efficient wing-kinematics. The results also helps in quantifying lift and thrust for potential wing-kinematics, so that one could select a suitable wing kinematics depending on the requirement.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

## OBJECTIVES:

Insects and birds use unsteady aerodynamics for their flight. At low Reynolds numbers, unsteady aerodynamics offers many advantages over fixed wing flight like high maneuverability, high lift at large angles of attack and hovering-flight. With many years of research, principles of steady aerodynamics (2-D aerofoil and finite wings) applicable to a fixed wing aircraft are quite well understood. In contrast, basic engineering principles needed for an optimum design of small mechanical objects (MAVs), which can use unsteady aerodynamics for propulsion and lift, have not yet been established. In earlier work we have demonstrated using flow visualization and 2-D numerical simulations that asymmetric flapping and controlled wing flexibility could produce sustained lift and at times enhance the lift generation in flapping flight.

Objective of the proposal is to measure forces generated by flapping test-rig for rigid and wings having controlled flexibility to identify an efficient wing-kinematics. The results also helps in quantifying lift and thrust for potential wing-kinematics, so that one could select a suitable wing kinematics depending on the requirement.

## STATUS:

Funding from the project has resulted in estimation of forces during flapping flight. A test-rig that can execute simple wing kinematics—*asymmetric-flapping* and can operate at different frequencies (Figure 1) is used along with a multi-axis force sensor [Figure-2] for this purpose.

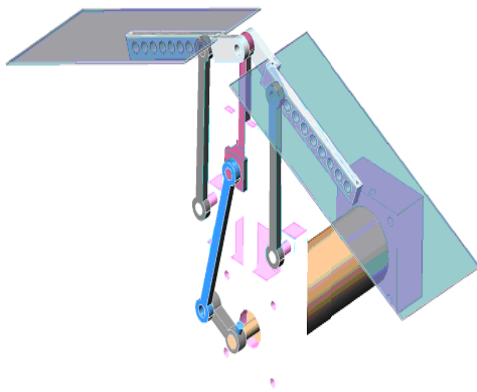


Figure-1: Schematic diagram of flapping test rig that can execute asymmetric flapping.

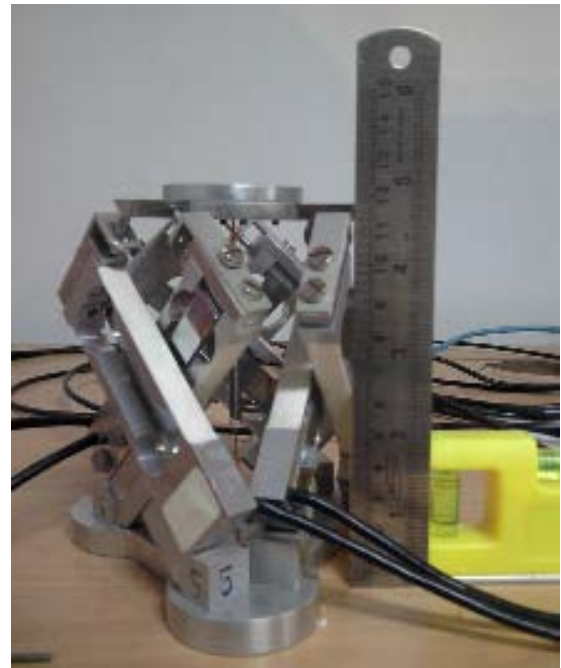


Figure-2: Multi-axis force sensor that can measure three force components and three moments.

## ABSTRACT:

In recent times, research in the area of flapping flight has attracted renewed interest with an endeavor to use this mechanism in Micro Air vehicles (MAVs). For a sustained and high-endurance flight, for having larger payload carrying capacity, we need to identify a simple and efficient flapping-kinematics. Earlier studies in our group, using flow visualization and 2-D simulations, have shown that a new mechanism— *asymmetric-flapping* could generate sustained lift [Refer to Figure-3]. This wing kinematics is simple and our studies further indicated that by introducing optimal wing flexibility and with a suitable wing-inclination the lift coefficient can be doubled and identifying most optimum asymmetry-ratio for which lift produced will be maximum [Figure-4] . Our 2-D simulations resulted in charts of estimated lift-force for given flapping frequency and wing size during optimum flapping.

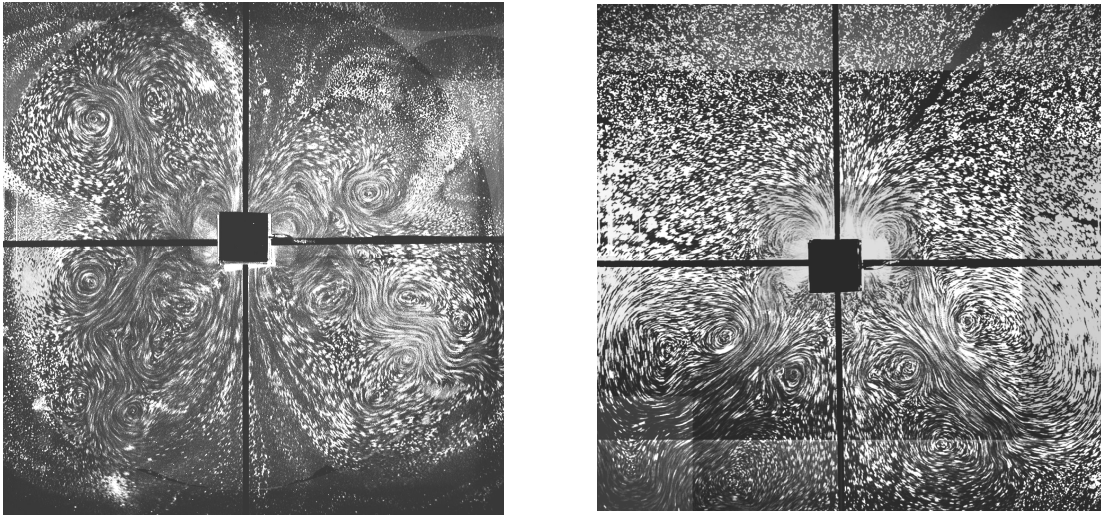


Figure-3: Streak photograph of flow field generated during symmetric-flapping (left panel) and asymmetric-flapping (right-panel). During asymmetric-flapping fluid is sucked from the sides and continuously pushed down, which indicates that a net upward force must be experienced by the flapping-wings.

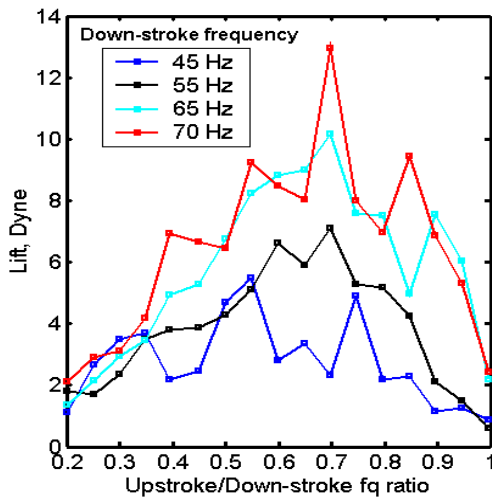


Figure 4: Variation of lift force with asymmetric ratio AR, for various down-stroke flapping frequencies. Wings are rigid and executing flapping motion with  $\phi = -20^\circ$  and amplitude of flapping,  $2\theta = 80^\circ$ . Chord length of the wing is 1cm and estimated force is for a wing of 1cm length into the plane of the figure.

Thus the project was started with an aim to develop a flapping test-rig having capability to execute asymmetric-flapping and a multi-axis force balance to measure forces while the test rig is mounted on the balance and executing flapping motion. This exercise helps in direct verification of adoptability of *asymmetric-flapping* into MAV design. The challenges were to make the test-rig lightweight and have provision to operate with different wings and frequencies. On the multi-axis balance side, we have to make the balance strong enough to take the dead load of the test-rig and at the same time has sensitivity to measure all components of small-forces and moments generated at flapping frequencies. Also, for carrying out analysis the data rate should be fast enough to integrate force-time curves to obtain net-force generated in a cycle.

As part of the project six-axis balance was made (Figure-2). Measuring aerodynamic load alone is a challenge because the balance always measures total forces produced by the test rig. The total force includes inertia of the various links and the wings in the test-rig, reactionary due to the motor torque and the aerodynamic forces from the wings. One could try to separate these inertial forces from the aerodynamic forces in two ways (a) measure the forces produced by the test rig and later carryout another experiment of force measurement in a evacuated enclosure difference between them would give aerodynamic load and (b) if the wings are lightweight, and their inertial loads are negligible, then one can carryout experiments of force measurement with wings in the test-rig and later dismounting the wings and repeating the force measurements; difference in magnitude of forces in two cases will give aerodynamic-load. We adopted later method for force measurement (Figure-5).

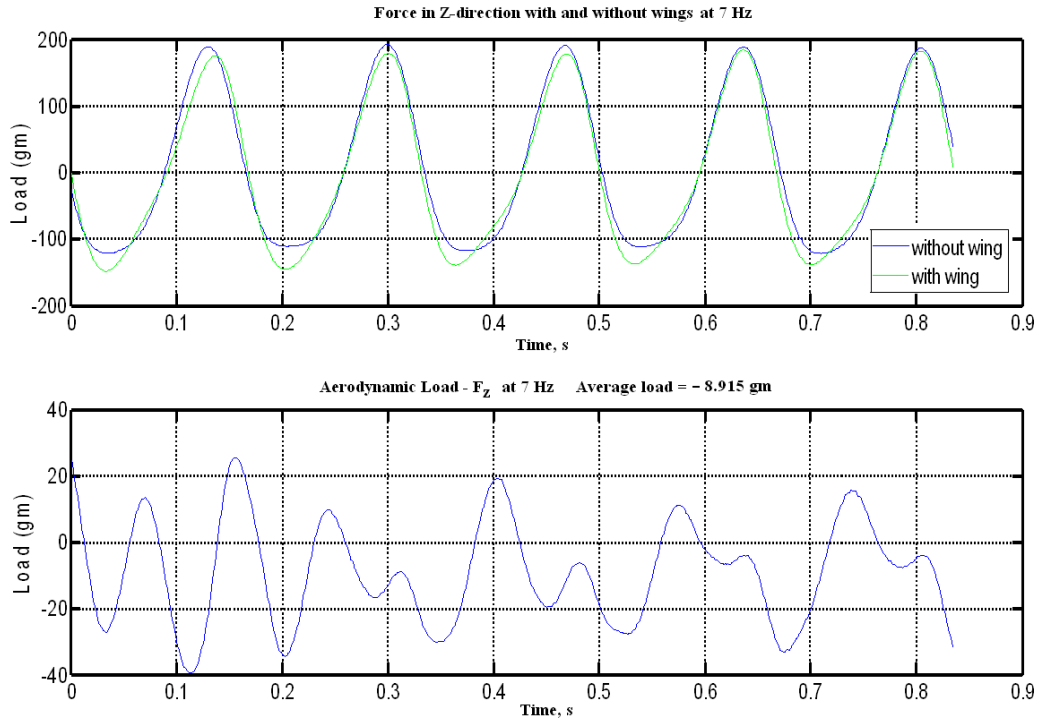


Figure-5: Variation of Z-component of force. Top panel indicates time variation of force measured with and without wings-flapping frequency is 7Hz. Bottom panel indicates the difference between these two cases, which represents time variation of aerodynamics lift-force.

It is evident from the results presented in Figure-5, that the aerodynamic lift is a small fraction (10-15%) of total dynamic load. Thus it is always better to have lightweight test-rig. Preliminary results are tabulated in Table-1 below, indicating average forces ( $F_x$ ,  $F_y$  and  $F_z$ ) for different flapping frequencies.

TABLE-1

<b>Frequency (Hz)</b>	<b>Average load (<math>F_x</math> in gm)</b>	<b>Average load (<math>F_y</math> in gm)</b>	<b>Average load (<math>F_z</math> in gm)</b>
<b>3.65</b>	<b>0.417</b>	<b>0.663</b>	<b>-1.567</b>
<b>6.4</b>	<b>1.361</b>	<b>2.441</b>	<b>-6.213</b>
<b>7</b>	<b>5.304</b>	<b>8.087</b>	<b>-8.915</b>

#### PERSONAL SUPPORTED

Here is a list of people given who have worked through this project.

- (1) Mr. Siddharth Krithivasan      Research Student
- (2) Mr. Jaikrishnan Vijayakumar   Research Assistant
- (3) Two summer interns-      Mr. Siddharth AV and Mr. N Harsha

#### PUBLICATION:

A parametric study of new lift generation mechanism in flapping flight: Experiments and numerical simulations, Shreyas J. V., Devranjan S., and Sreenivas K. R. *International Symposium on Applied Aerodynamics and Design of Aerospace Vehicle (SAROD 2009) December 10-12, 2009, Bangalore, India* [Invited talk]

Experimental and numerical simulations for the quantification of lift in flapping flight, Siddharth, K., Dwarakanath, T.A, and Sreenivas K. R., *6<sup>th</sup> International Conference on Intelligence Unmanned System* held in Bali Indonesia, during 3-5 November 2010

Lift Production through asymmetric flapping, Shreyas JV and Sreenivas K R, *62<sup>nd</sup> Annual meeting of APS DFD, Minnesota, USA, November 2009.*

Identification of new lift generation mechanism in flapping flight, Shreyas JV, Devaranjan S and Sreenivas K R, a manuscript being submitted to *Physics of Fluid*.

Apart from these; I have also given seminars on this topic at IIT-Kanpur, NIT-Kurkshetra MSRIT and AIT Bangalore, University of Oregon, Corvallis, OR USA for disseminating results from our study and to attract students for research program at JNCASR.

#### INTERACTION:

- (1) Dr. Michael V, Ol
- (2) Prof. Wei Shyy
- (3) Dr. Srigrarom Sutthiphong
- (4) Prof. Michael Dickinson
- (5) Dr. Devesh Ranjan
- (6) Dr. Sourabh Apte
- (7) Prof. George Barbastathis

#### INVENTION

The research proposal is for basic understanding of various lift generation mechanisms that could be used for MAV applications. Effort of our group on this topic has helped in identifying following basic facts about flapping flight:

- (a) A simple wing-kinematics of *asymmetric-flapping* can produce sustained lift. We also find many birds and insects have adopted this in their flapping, however we do not yet know relative importance of that in their lift production.
- (b) While flapping at frequencies above 40 Hz, keeping the asymmetric-ratio (that is ratio of down stroke period to up stroke period) around 0.7 will give maximum lift.
- (c) For a given flapping frequency, flapping amplitude and mean position of the wing there is an optimal wing flexibility for which lift produced will be maximum.

Asymmetric-flapping as a lift-generation mechanism is first identified by research in our group.

#### HONORS/AWARDS

NIL

